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Current Opinion in Environmental Science & Health

Vegetation and soil degradation in drylands: Non linear feedbacks and early warning signals

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Abstract

Anthropogenic activities and climate change are imposing an unprecedented pressure on drylands, increasing their vulnerability to desertification. The spatial organization of the sparse vegetation cover is fundamental for the healthy function of the system, and disturbances can trigger cascading feedbacks leading to catastrophic system collapse. Here we discuss some of the latest research aiming at understanding abrupt landscape transitions and possible non-reversible changes, as well as emerging research on the identification of early warning indicators of abrupt transitions to desert states. Robust indicators should take into account temporal system dynamics characteristics, vegetation organization/patch size distribution, functional connectivity measures and human intervention effects.

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Current Opinion in Environmental Science & Health 2018, **5**:67–72

This review comes from a themed issue on **Sustainable soil management and land restoration**

Edited by **Paulo Pereira** and **Juan F. Martínez-Murillo**

For a complete overview see the Issue and the Editorial

https://doi.org/10.1016/j.coesh.2018.06.001

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Keywords

Drylands, Vegetation patterns, Thresholds, Desertification, Early warning.

Introduction

Anthropogenic activities and climate change are imposing an unprecedented pressure on landscapes worldwide. This pressure is particularly alarming in drylands that are vulnerable to desertification [1]. Desertification can potentially affect 38% of the world's population, and is therefore one of the most serious issues facing many regions across the world [2]. Its global importance and potentially devastating effects were recognized by the United Nations international through establishment of conversion framework (United Nations Convention to Combat Desertification, UNCCD) established in 1994. Though the UNCCD framework has been in place for over two decades, understanding of the processes involved in desertification and the identification of early warning signals of transitions to degraded states are still a challenge [1].

Regime shifts are abrupt landscape transitions, which in drylands (and also in other systems) have been sometimes linked to the presence of hysteresis. Restoration in landscapes where degradation follows a hysteresis cycle is difficult and very costly [3]. The pressing need to avoid these type transitions to degraded states has recently triggered substantial research focusing on the development of early warning indicators of regime shifts [3,4]. In this opinion, we will first briefly discuss the research that, over the last couple of decades, has advanced our understanding on non-linear feedbacks and function of semiarid landscapes. This work has enabled the identification of early warning indicators of desertification that will be discussed in more detail, particularly focusing on the recent progress.

Non-linear feedbacks between vegetation, soil properties and water redistribution

Drylands, which are classified as areas with an aridity index below 0.65 (ratio between rainfall and potential evapotranspiration) are characterized by highly unpredictable rainfall and extreme solar radiation [2,5]. These extreme conditions are responsible for the presence of a sparse vegetation cover organized as a mosaic of patches of vegetation surrounded by bare soil, as water availability is not enough to support a contiguous plant cover. The limited amount of water and its key role for the sustenance of vegetation patches have triggered a large number of studies to better comprehend the effect of rainfall variability on ecosystem stability and landscape processes [6,7]. It also highlighted the need for an improved understanding of the spatial redistribution of water in the landscape over a wide range of scales as the main driver for the emergence of vegetation patterns [8–11]. An important mechanism deemed responsible for the anisotropic distribution of available water is the presence of higher infiltration rates in vegetation

patches, which is induced by roots, macropores, improved soil aggregates and/or decreased evaporation due to plant canopies [12,13]. The runoff produced in the bare areas infiltrates in the vegetated patches, and therefore the water captured in these vegetated areas can be much larger than incoming rainfall. This mechanism is self-reinforcing as it increases water availability and growth in the vegetated patches. Runoff-runon redistribution from bare soil source areas to sink patches is therefore of key importance for maintaining healthy (functional) drylands. Preserving this natural redistribution of resources is of key importance for the maintenance of hillslope functionality of drylands [10,14].

Though it is now widely recognized that the patchy vegetation cover emerges from nonlinear feedbacks between water and biotic processes [8,11,13,15–18], it is also important to emphasize that the redistribution of resources is mediated by the coevolving soil and landforms [19,20]. When vegetation patches (or water sinks) are altered by external disturbances (like droughts, increased grazing or wood harvesting) leading to loss of plant cover, the hydrologic connectivity between of the landscape is increased [14]. Runoff increases and is lost from the system, and therefore becomes unavailable for vegetation growth potentially leading to severe erosion [10].

Soil erosion feedbacks

Disturbances leading to an increase in bare soil connectivity can trigger severe erosion due to several processes that have the potential to reinforce degradation. Increased runoff increases the erosion potential directly by increasing shear stresses and by decreasing the protective effect of vegetation on the soil surface (i.e., increased erodibility [9]). Increases in erosion and runoff triggered by changes in vegetation amount and distribution can eventually lead to the development of rills and gullies [9,21]. This effect can be particularly critical in high slopes due to the presence of high shear stresses, which can produce changes in landform patterns due to flow concentration [9]. These changes can subsequently induce further changes (reduction) in the vegetation cover, decreasing the resistance to flow and water holding capacity as the soil becomes thinner, ultimately increasing flow velocity reinforcing the positive erosion feedback [14,22]. Vegetation also affects wind-driven erosion processes, as the reduction of vegetation cover reduces both sediment capture and erosion protection [10,23,24]. The main characteristic of wind-driven erosion is that, unlike fluvial erosion, small and frequent wind events are the main contributors to the overall sediment budget [25].

The degradation mechanism, induced by positive feedbacks between erosion processes and vegetation [12,13,20,22,26–28] underscores the significance of understanding the coevolution of the landform-vegetation system structures in the analysis of dryland systems, not just at the event timescale but over decades or longer scales. Modelling can be a useful tool to study coevolution, as shown by Saco and Moreno-delas Heras [9], who studied the role of abiotic (relief, erodibility, and soil diffusion) and biotic (protective effect of vegetation on soil) factors on the coevolution of landforms and vegetation patterns in semiarid rangelands.

Degradation trends, early warning signs, shifts and thresholds behaviour

Due to the potentially devastating desertification effects induced by climate change and land use activities, the identification of early degradation indicators has been a topic of many recent studies [29–33]. In order to identify early warnings an improved understanding of the changes in landscape structures and function that lead to the desertification of drylands across the world is needed [1,14,29,34]. These changes may be gradual, abrupt or catastrophic (Figure 1). In this last case, the presence of hysteresis makes changes very difficultly to reverse. Non-reversible or persistent changes, also known as regime shifts [35], tend to generate extensive negative effects so their understanding and early identification is crucial to the design of useful management strategies [1]. A particularly important aspect that has led to many recent studies is the existence of degradation thresholds or tipping points in which the regime shift occurs in abrupt way, which makes the identification of early warnings particularly important.

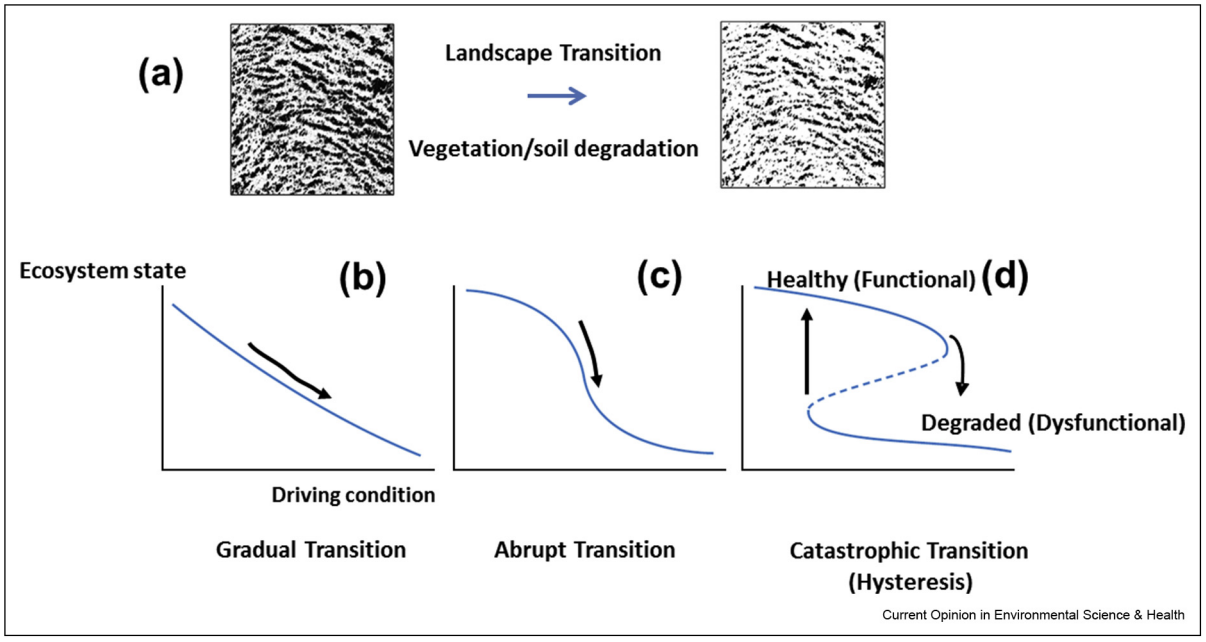
The analysis of temporal dynamics in different ecosystem (which may include landform or soil variables), such as increasing fluctuations, can provide critically relevant information for early warning signals of imminent shifts [30,36]. However, recent work has investigated another source of useful information for the identification of early warnings for shifts: the spatial organization of vegetation patterns.

Early warning indicators from spatial vegetation patterns and patch size distributions

As explained in previous sections, vegetation mosaics evolve from non-linear interactions between water, plants, soils and landforms and the resulting patterns can be considered as an emerging signature of the system. Recent studies suggest that changes in the patchiness of these patterns can be used as an indicator of proximity to a transition from a healthy functional to a degraded/desert state [4,14,29,37–40].

Initial theoretical studies found that patch size distributions of vegetation are such that most patches have smaller sizes and only very few patches have large sizes, and that these distributions follow a power law or scale-

Figure 1



(Adapted from Kefi et al. [39]): (a) Landscape transition from a healthy state to a degraded state with loss of vegetation and soil function. This type of transition in ecosystem state (for example vegetation cover, productivity, ecosystem or soil functionality) can occur gradually as shown in (b), following and abrupt change (c) or a catastrophic transition (d).

free vegetation patterns [16,17]. Departures from the power law (e.g. loss of large vegetation patterns due to disturbances like grazing) were proposed to be indicative of early warning of transitions to a desert state. Work by von Handerberg et al. [41] extended the theoretical analysis to account for areas displaying patch sizes with a given characteristic scale (depicted by a narrow distribution of patch sizes), as in the case of spotted banded patterns or banded patterns observed in nature [38].

These theoretical studies triggered a number of empirical studies that have taken advantage of the growing availability of remote sensing data, which enables the identification of high resolution vegetation patterns, and is increasingly becoming accessible at reasonable costs. Empirical studies are looking at various characteristics related to vegetation patterns, including not only patch size distributions but also simpler measures like total plant cover and more complex measures linked not only to the spatial arrangement of vegetation but also to plant–plant interactions and ecosystem functionality. For example, Xu et al. [42] and Alados et al. [43] demonstrated the feasibility of using spatial metrics of vegetation patterns (skewness of the patch-size distribution and plant aggregation) for the development of early warning signals accounting for the role of plant–plant interactions and local facilitation mechanisms. A recent study by Berdugo et al. [29] tested the usefulness of using patch size distributions as indicators of degradation and ecosystem functionality for a large number of dryland sites worldwide. They computed an index of ecosystem functionality as an average of values for functions related to different soil nutrients, which was assumed to be a good indicator of soil fertility and plant productivity. They found a bimodal distribution of this index suggesting two alternative states of ecosystem functionality, which was only reflected on the patch size distribution, but not captured by vegetation cover. More importantly, these results suggested that systems that followed a power-law distribution are controlled by different mechanisms (i.e. facilitation and productivity) than those that deviated from the power law [40].

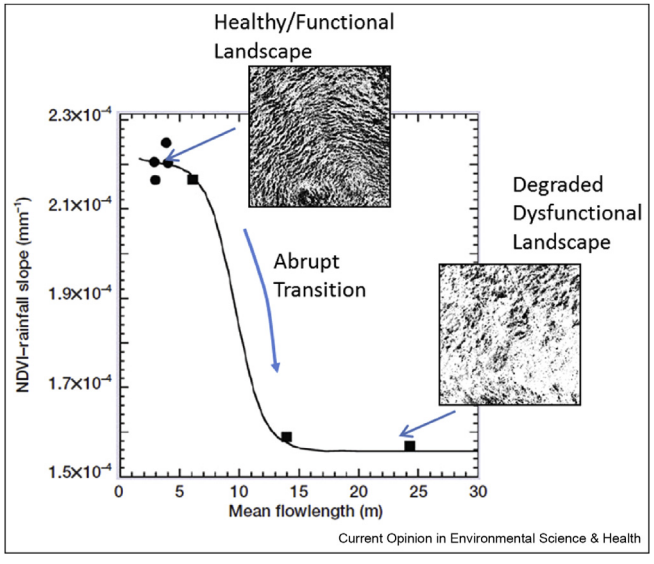
Early warning indicators and coevolving connectivity measures

Though these recent studies have underlined the value of using patch size distributions to develop early warning indicators of degradation, alternative studies have also demonstrated the need to integrate other measures associated to coevolving system processes (e.g., surface water redistribution, soil erosion and evolving landforms [9]). For example, the work of Moreno-de las Heras et al. [38] looking at patch size distribution of regular banded Mulga landscapes in Australia, demonstrated the importance of accounting for landform anisotropy (i.e., topography that prescribes the redistribution of sediment and hydrology) for the analysis of patch size distributions. Anisotropic effects can also emerge from differences in insolation driven by landscape aspect

which greatly influences vegetation patterns, runoff generation and erosion processes [44]. These types of anisotropy or those arising from heterogeneity in external perturbations (i.e., grazing, logging [31,45]) can be easily incorporated into the analysis of landscape hydrological connectivity [14].

Hydrological and sediment connectivity determine the redistribution of water and sediments and therefore the healthy function of drylands [46,47]. An increase in connectivity (i.e., through vegetation removal) can trigger loss of the plant patches ability to obstruct/capture the runon for plant growth [48,49]. This reduction in water retention and the associated loss of ecosystem functionality (i.e., productivity) can induce non-linear threshold behaviour and tipping points in dryland landscapes [8,11]. To this end, recent research has looked at the role of hydrological connectivity for the maintenance of a healthy landscape function, and its potential use for the identification of transitions, threshold behaviour and early warning indicators in drylands [10,14,21,50,51]. For example, for the case of the banded Mulga landscapes of Australia Moreno-de las Heras et al. [14] showed that increases of hydrologic connectivity can trigger non-linear feedbacks leading to degradation as loss of landscape functionality following threshold-like behaviour (Figure 2). More recently Rodriguez et al. [51], using the flowlength index [21] as the metric for connectivity, derived expressions for expected values of connectivity as a function of landscape cover. Their results suggested that deviations from the expected connectivity index could be used as early warning signals for imminent transitions to a degraded state.

Figure 2



(Adapted from Okin et al. [10]) Variability of rainfall-use efficiency (as a proxy for landscape functionality) plotted against flowlength (a metric of hydrological connectivity [21]) for different semiarid site in the Northern Territory, Australia (see Ref. [14] for more details). Rainfall-use efficiency was computed from the slope of the normalized difference vegetation index [NDVI]–rainfall relationship. Landscape-level vegetation responses to precipitation differ between disturbed plots (squares) with high mean flowlength and undisturbed plots (circles) with low mean flowlength. The plot shows an abrupt transition (threshold-like behaviour) in landscape functionality as hydrologic connectivity increases.

Early warning signals accounting for social feedbacks

The influence of humans on their environment is continuously increasing, not only due to the impact of development pressures but also due to their awareness of those impacts and their effort to mitigate them. Coupled human-environmental systems typically exhibit a wider variety of regime shifts [52,53], and the early warning signals may be more difficult to identify [52,54]. In fact, some complex coupled systems may not display early warnings at all, as several factors may combine simultaneously ("perfect storm") and produce system collapse [54,55]. In other cases, human feedback can mute the early warning signals due to conservation or management efforts, and if those efforts occur when the system is close to collapse it remains close to tipping point in perpetuity [53] or display signals of hidden collapse [56]. To date, most of the work on early warning signals in coupled human–environment systems has been done through modelling and descriptions of collapse after the event. Research on coupled systems has great potential to improve our understanding of degradation in drylands and the development of early warning indicators.

Summary and conclusions

Recent research has shown that preserving the spatial organization of vegetation is critical for the sustainable management of drylands. This concept is in line with the recent recognition of the superior benefits of nature-based approaches for management and restoration of ecosystems [57]. The structure of vegetation patterns is intrinsically linked to the healthy functioning of drylands, and any attempt to restore degraded rangelands needs to incorporate this concept [10,58]. However, though the restoration efforts are extremely important and needed, it is also particularly important to implement managing strategies to avoid the need for later restoration. This requires the development and implementation of adequate monitoring indicators for ecosystem health [59,60] and robust early warning indicators for abrupt transitions [61,62]. As we explained earlier, new approaches are being developed to provide early warning signals of ecosystem transitions to be used in monitoring. These techniques, based on different indexes that capture the metrics that characterize the spatial organization of healthy ecosystems, are being developed and tested in drylands across the world. However, more research is still needed to develop techniques based not only on soil and vegetation

patterns but also on the understanding of how these structures might co-evolve in response to disturbances. This type of understanding can only be gained by combining recent advances in both modelling of coevolving systems [11,20,28,44] and indicators of landscape functionality [31,40,43,46–51,57].

Conflict of interest statement

None declared.

Acknowledgements

We acknowledge support from an International Visiting Fellowship from the University of Newcastle awarded to Saskia Keesstra and the COST Action ES1306 (Connecting European Connectivity research). P. Saco acknowledges support from the Australian Research Council through grants FT140100610 and DP140104178. Mariano Moreno-de las Heras is beneficiary of a Juan de la Cierva fellowship (IJCI-2015-26463) funded by the Spanish Ministry of Economy, Industry and Competitiveness.

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